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Modeling of Observed Permanent Deformation at La Villita Dam

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SYNOPSIS: The observed behavior of La Villita dam in Mexico during five different earthquakes which have occurred in the period 1975–1985 is analyzed. Asymmetry observed in the recorded crest acceleration time histories is interpreted to be due to localized stick–slip behavior below the recording instrument. Yield acceleration associated with each stick–slip event can be inferred directly from these crest records. Values of observed average yield accelerations for the November 15, 1975 and September 19, 1985 earthquakes are used to predict the observed horizontal displacements during these earthquakes. Response of other soil systems involving stick–slip deformations during dynamic loading is also briefly discussed.

INTRODUCTION

La Villita dam is a sixty meters high earth and rock fill dam located 350 km south west of Mexico City, Mexico. Six major earthquakes ($4.9 \leq M_L \leq 8.1$) at epicentral distances of 10 km to 121 km have subjected this dam to substantial dynamic loads. Five of these earthquakes (the most recent being that of September 19, 1985 which also caused extensive damage in Mexico city) have contributed to significant measured vertical and horizontal displacements in the dam. In addition, bedrock and crest acceleration records for the November 15, 1975 and September 19, 1985 earthquakes are available. The recorded dam crest acceleration time histories are peculiarly asymmetric. In this paper, the observed La Villita crest response is compared to the response of a block sliding on an inclined plane. The block response is measured in simple laboratory experiments and is calculated using a yielding sliding block model. This comparison reveals that the asymmetry in the crest acceleration records is due to stick–slip deformation localized below the crest strong–motion instrument. Yield accelerations can be inferred directly from these crest acceleration records [Elgamal et al, 1990]. These yield accelerations are used in combination with crest acceleration time histories calculated using a 1–D nonlinear shear wedge model to predict the observed permanent displacements due to the November 15, 1975 and September 19, 1985 earthquakes. Finally, the significance of stick–slip as a deformation mechanism in other civil engineering structures is discussed.

LA VILLITA DAM

La Villita, a 60 meters high earth and rock fill dam, is located in Mexico 13 Kilometers upstream from the mouth of the Balsas River which empties into the Pacific Ocean [Comision Federal De Electricidad, 1980, 1985, 1987]. It was constructed in the period between 1964 and 1968. An alluvial layer (mixture of boulders, gravel, sand and silt), of varying thickness (maximum thickness of 70 meters) lies between the embankment and bedrock (Figure 1a). During its construction the dam was instrumented with inclinometers and accelerographs (Figure 1b). Horizontal and vertical displacements (Figure 2)

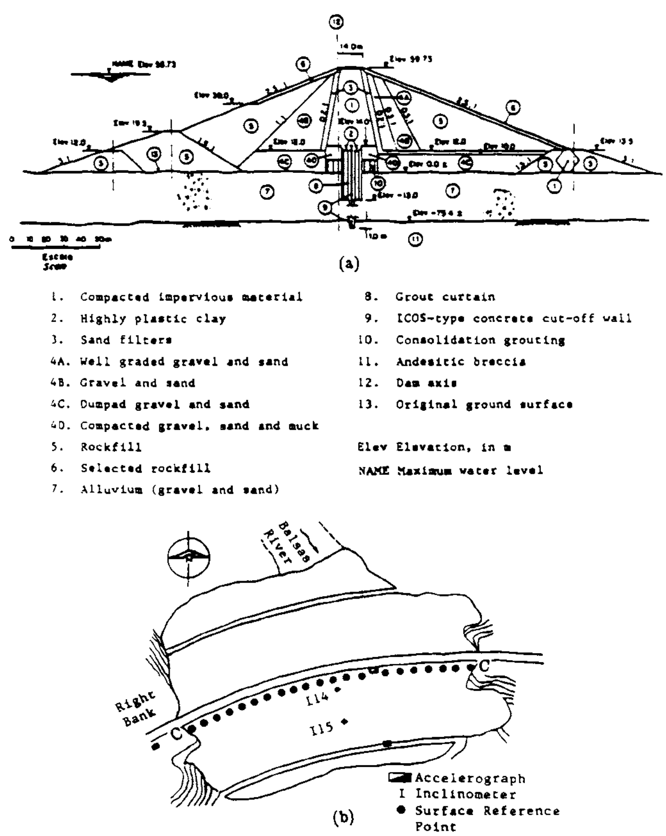

Figure 1. La Villita Dam: a) maximum cross section; b) location of accelerographs, inclinometers, and surface reference points [Comision Federal De Electricidad, 1980, 1985, 1987].

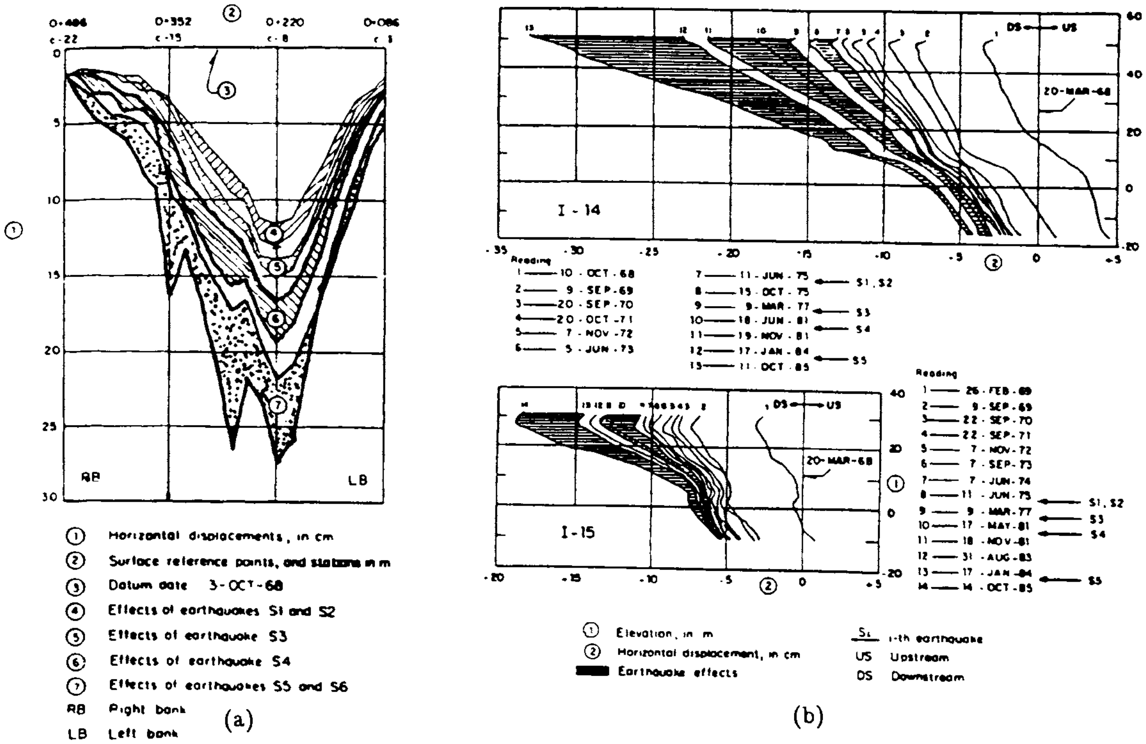

Figure 2. La Villita Dam: recorded downstream slope horizontal displacements [Comision Federal De Electricidad, 1980, 1985, 1987].

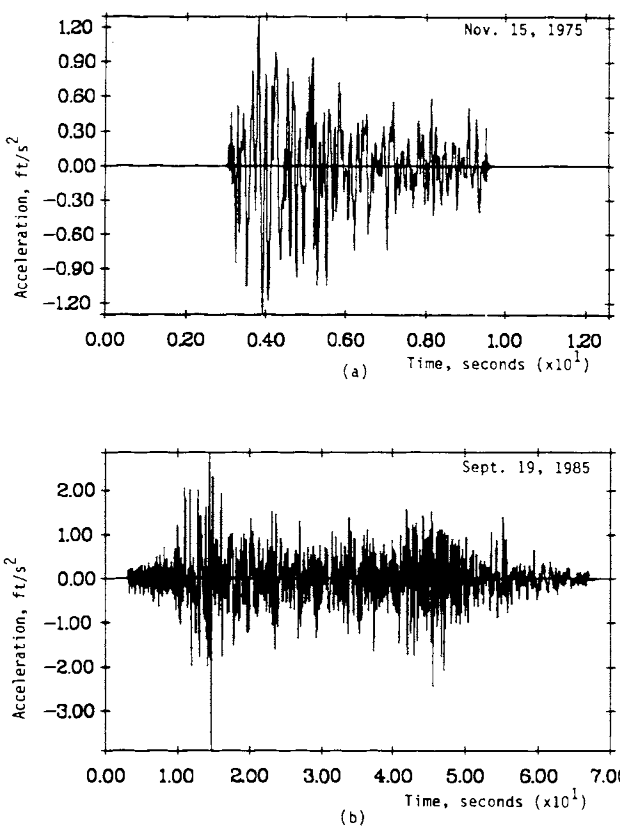

Figure 3. La Villita Dam: time history of accelerations recorded at bedrock; a) November 15, 1975; b) September 19, 1985. [Comision Federal De Electricidad; 1980, 1985, 1987].

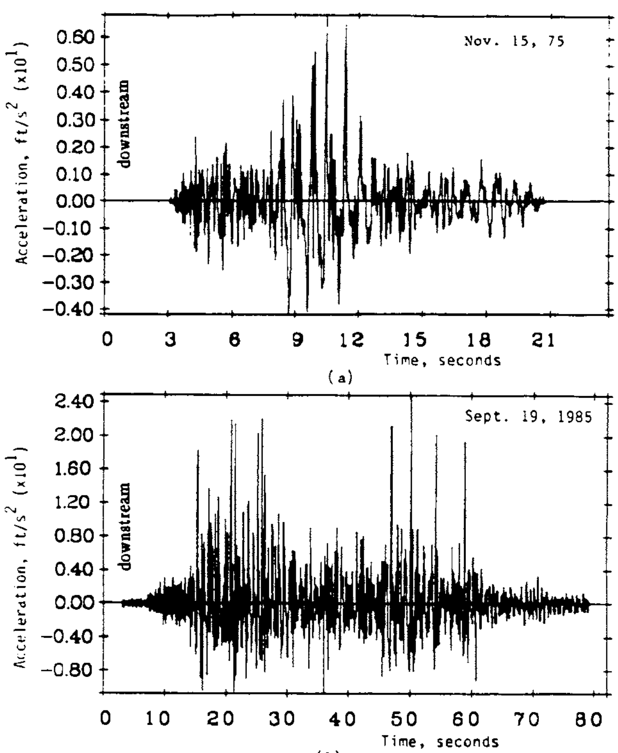

Figure 4. La Villita Dam: time history of accelerations recorded at dam crest a) November 15, 1975; b) September 19, 1985. [Comision Federal De Electricidad; 1980, 1985, 1987].

as well as bedrock (Figure 3) and crest acceleration histories (Figure 4) have since been recorded during several subsequent earthquakes. The recorded crest acceleration histories exhibit a peculiar asymmetry similar to that which appears in the response of a sliding block on an inclined plane.

THE SLIDING BLOCK MODEL

The sliding block approach is used to represent embankments subjected to earthquake loading where the applied cyclic stress plus the existing static shear stress exceed the shearing resistance of the soil along a failure plane. It was introduced by Newmark [Newmark, 1965] who assumed that the movement of a soil mass above a well defined failure surface occurs when the shear strength of the soil is exceeded and during the period over which it is exceeded. The response of a rigid block on an inclined plane subjected to a horizontal input acceleration, a_h, was investigated both experimentally and analytically in an earlier publication [Elgamal et al, 1990]. The magnitude of the yield acceleration in the horizontal direction A_y – for sliding in the downslope direction – is given by:

$$A_y = \{g(\mu(\cos\beta + a_h \sin\beta / g) - \sin\beta\} / \cos\beta \qquad (1)$$

where g is gravity acceleration; β is angle of slope inclination; and μ is friction coefficient.

The yield acceleration obtained from Eq. 1 is dependent on the amplitude of input motion (component of this motion in the direction perpendicular to the slope, i.e., $a_h \sin\beta$). This yield acceleration therefore varies with variations in input motion a_h (e.g Fig. 5). A

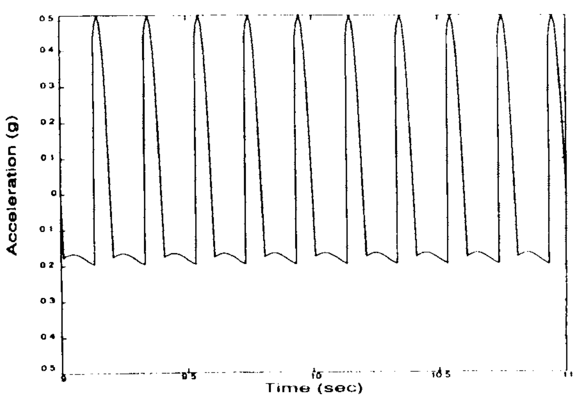

Figure 5. Computed absolute acceleration of block parallel to slope.

constant yield acceleration is obtained in a simplified version of the above sliding block model in which input acceleration is chosen parallel to the direction of sliding. In such a case, the magnitude of yield acceleration A_y in the direction of sliding is given by:

$$A_y = g(\mu\cos\beta - \sin\beta) \qquad (2)$$

The following equations describe this simplified model (Figure 6):

$$(\ddot{x} + \ddot{u}) + P = 0 \qquad (3)$$

$$P = F/M \qquad (4)$$

$$\begin{aligned} F(t+1) &= F(t) + K(x(t+1) - x(t)) \text{ for } F(t+1) < F_y \\ &= F_y \qquad \text{otherwise} \end{aligned} \qquad (5)$$

where, M is the mass of the block, x is the displacement of the block relative to the slope, $\ddot{u}$ is the input slope acceleration, F is a nonlinear elastic-perfectly plastic force following the theory of incremental plasticity, F_y is the yield force (in the downslope direction), beyond which, the block undergoes permanent relative displacement, t is time, and a superposed ($\dot{}$) denotes time differentiation.

A numerical example [Succarieh, 1990] showing the response of a sliding block (Eqs. 3-5) subjected to harmonic excitation applied in the slope direction is shown in Figure 7. In this example, $(K/M) = 10^6$ radians/sec^2, $\ddot{u} = 0.55 \cos 2\pi t$ m/sec^2, $P_y = -0.36$ m/sec^2, and step-by-step numerical integration is used.

A laboratory experiment is also performed to measure block stick-slip response. A metal block is placed on the surface of a tilted 1-directional shake table which is forced into harmonic motion with an amplitude chosen low enough such that the metal block slides in the downward direction only. Accelerometers are attached to the metal block as well as to the inclined surface and the resulting acceleration response is shown in Figure 8. It is noted that a transient acceleration response (spike) is observed in Figures 7a and 8 at the end of each slip phase.

Based on the presented experimental and numerical response, the following salient characteristics associated with block stick-slip response are observed:

1. During the "stick" phase, the absolute acceleration of the sliding block is the same as that of the slope (or the absolute acceleration of the sliding mass is the same as that of the dam).

2. During the "slip" phase, the absolute acceleration of the block departs from that of the slope. A constant yield absolute acceleration is observed for the perfect plasticity numerical idealization (Figure 7a) and a fairly constant value is observed in the experiment (Figure 8). The yield acceleration is seen in (Figures 7a and 8) to be smaller in magnitude than the input acceleration (slope or dam acceleration) in the upslope direction opposite to the yield direction. This behavior is similar to that observed at the crest of La Villita Dam (Figure 4). The available crest records at La Villita, therefore, reveal yield accelerations associated with the resulting stick-slip events. An average value of these yield accelerations for the earthquakes of

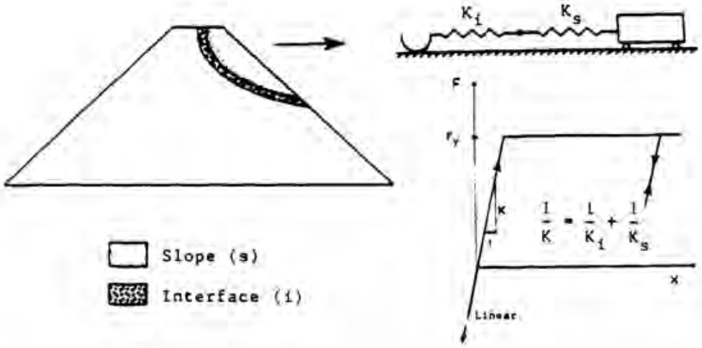

Figure 6. Flexible sliding block modeled as SDOF.

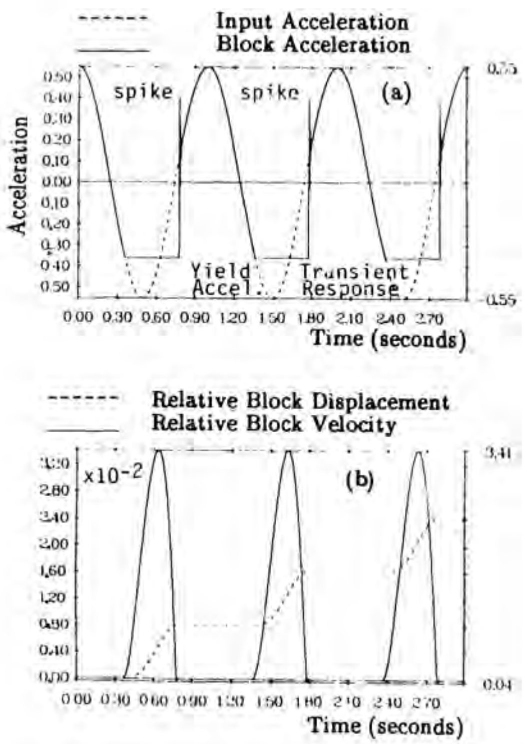

Figure 7. Calculated sliding block response.

November 15, 1975 and September 19, 1985 is shown in Table 1. A comparison between Figure 4 and Figure 7 reveals that the La Villita crest records of Figure 4 are positive in the downstream direction and negative in the upstream direction.

3. A sharp spike is observed at the end of each sliding phase due to additional dynamic excitation of the sliding mass triggered by the reunion of the sliding mass with the dam (Figures 7a and 8). The abrupt change in inertial force associated with this reunion may also cause a recording strong motion instrument (or accelerometer) to overshoot the response.

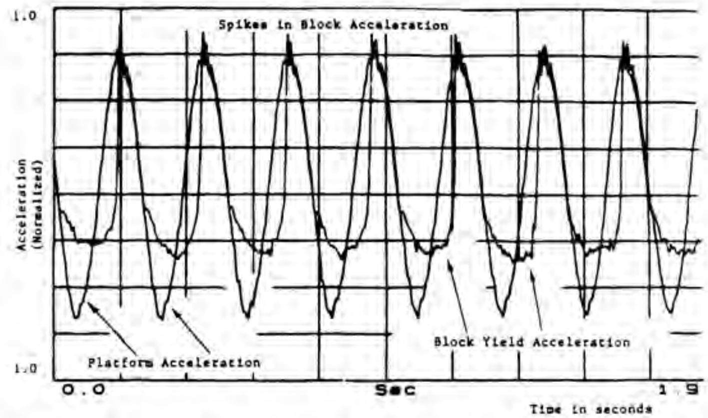

Figure 8. Experimental response: acceleratior time history.

In order to investigate this overshoot, a analytical study is conducted in which a stron ground motion instrument is idealized as a SDO oscillator with damping ratio ξ = 0.7 an natural frequency = 50 Hz. Input to th instrument is chosen as the response of Newmark-type sliding rigid block. Based on thi study, (under steady state conditions) it i found that an overshoot of about 14 % may occu (Figure 9).

4. The value of yield acceleration associatec with a particular sliding event depends on th acceleration component perpendicular to th failure surface. Changes in the value of yielc acceleration observed at the crest of La Villit dam (negative part of crest records shown ir Figure 4) may be attributed to such an effect.

In the next section, the sliding block mode described above is used in combination with the observed yield accelerations (Table 1) tc predict the observed La Villita dam crest horizontal deformation during the November 15, 1975 and September 19, 1985 earthquakes. Input motion to the sliding block model is taken as the dam crest acceleration computed by a dynamic 1-D earthdam shear wedge model.

COMPUTATION OF LA VILLITA DAM EARTHQUAKE RESPONSE

In this section, an attempt is undertaken to numerically estimate the measured localized crest horizontal displacements utilizing the available bedrock (input) acceleration records along with the yield acceleration(s) observed from the actual recorded crest acceleration time histories (Table 1). These crest records depict yield acceleration magnitudes as pointed earlier, and are to be compared to the response of a sliding block. An input motion to the sliding block must first be defined however. In order to maintain simplicity, the crest response computed by a dynamic earth dam numerical model will be chosen as input motion to the sliding block analysis. Permanent displacement accumulated by the sliding block will then be compared to that observed near the dam crest. It is emphasized that the available crest records are the response of a sliding mass and hence correspond to the sliding block response rather than to its input. Sequence of

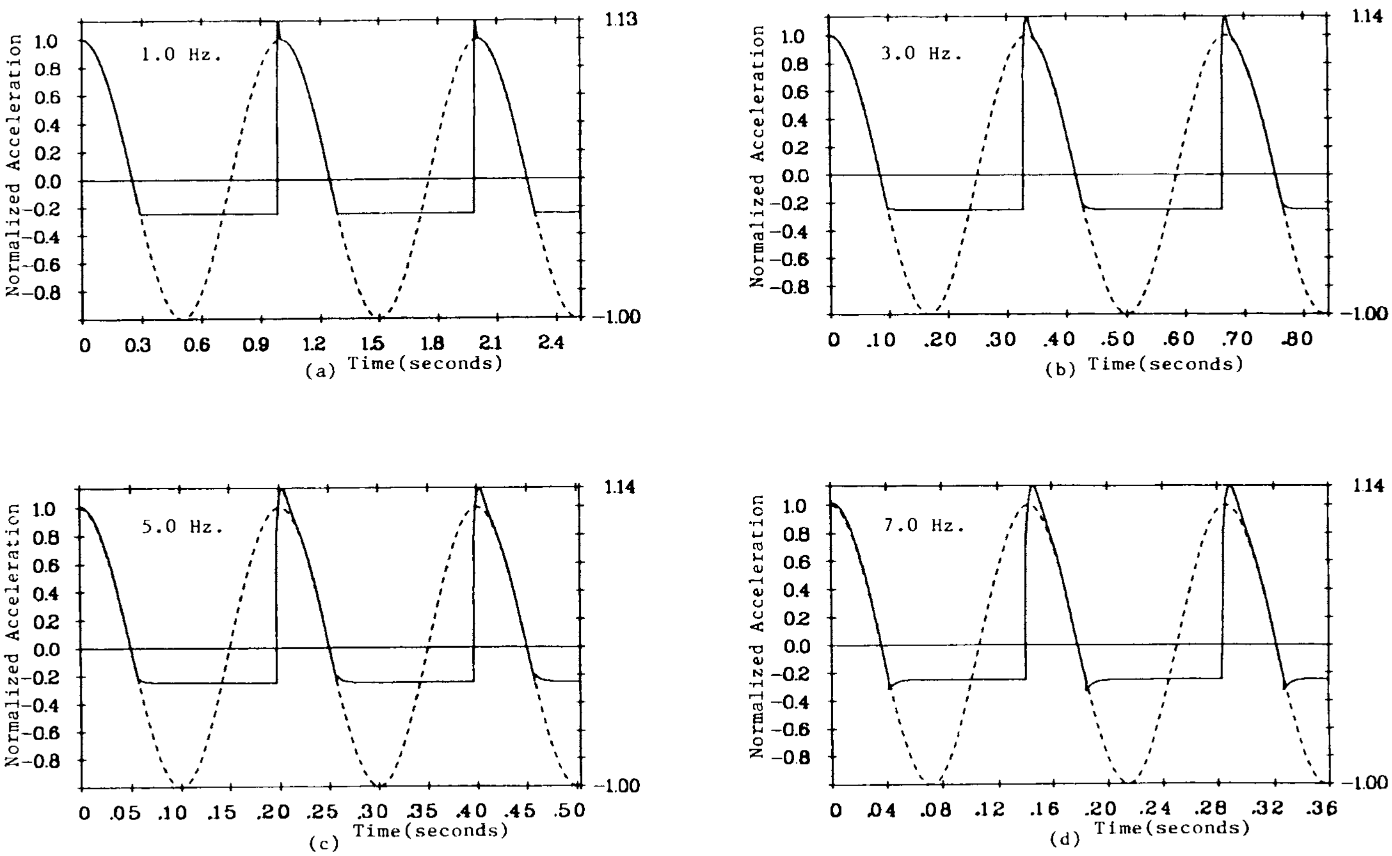

Figure 9. Overshoot acceleration response at various harmonic excitation frequencies due to strong motion instrument dynamic characteristics (dashed line is input and solid line is response).

calculations will proceed as follows (Figure 10):

Step No. 1: Calculate crest acceleration due to bedrock input acceleration using 1D earth dam numerical model.

Step No. 2: Use calculated crest acceleration as input to sliding block model and calculate block displacement and acceleration.

Total displacement from steps 1 and 2, and block acceleration, are then to be compared to those actually observed at the dam crest.

Response of intact dam (Step No. 1):
A simplified efficient model for the nonlinear hysteretic response of earth dams is used herein. The dam is modeled as a 1D hysteretic inhomogeneous shear-wedge which permits horizontal shear deformation only [Elgamal et al, 1988]. In this investigation the dam is idealized to have the following characteristics: h = 262 ft, which accounts for the presence of the underlying alluvial deposit, ρ = 3.88 lb sec^2/ft^3 and G_0=3280000 lb/ft^2. Useful bedrock acceleration histories recorded at the dam right bank are only available for the earthquakes of November 15, 1975, (0.042g peak acceleration) and September 19, 1985 (0.12g peak acceleration). Using the upstream-downstream component of these records as input, the corresponding computed displacement and acceleration crest response of the intact dam is shown in Figures 11 and 12. It is obvious from Figure 11 that essentially no permanent displacement has accumulated in contrast to the values actually observed (Table 1). In addition, the computed crest acceleration records (Figure 12) do not display the directional magnitude asymmetry similar to that actually observed.

Sliding block analysis (Step No. 2):
The crest acceleration time histories (Figure 12) obtained from Step No. 1 for the November 11, 1975 and September 19, 1985 earthquakes are now used as input to the sliding block model. The calculated permanent displacement time histories are superposed on the crest displacement time histories obtained from the 1D dynamic analysis of the dam (Figure 11) and the resulting plots are shown in Figure 13. Acceleration response of the sliding block is shown in Figure 14. Directional bias or asymmetry appears since the acceleration peaks on one side of the record are totally truncated beyond the selected yield acceleration magnitude. The calculated permanent displacement at the end of each earthquake (Figure 13) are found to be in the neighborhood of the corresponding observed horizontal displacements shown in Table 1. In 1975, it is

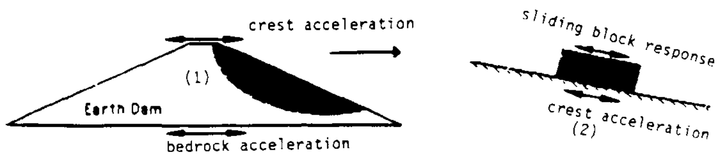

Figure 10. Sliding block model.

believed that two earthquake events (October 11 and November 15, 75) have contributed to the observed horizontal displacement since yielding exists in the corresponding crest acceleration records [Elgamal et al, 1990]. The calculated permanent displacement due to the November 15, 1975 earthquake (Figure 11a) is about half that observed (Table 1) since it corresponds to one of the two 1975 earthquakes only. The calculated permanent displacement due to the September 19, 1985 earthquake appears to be slightly less than the observed value (Table 1).

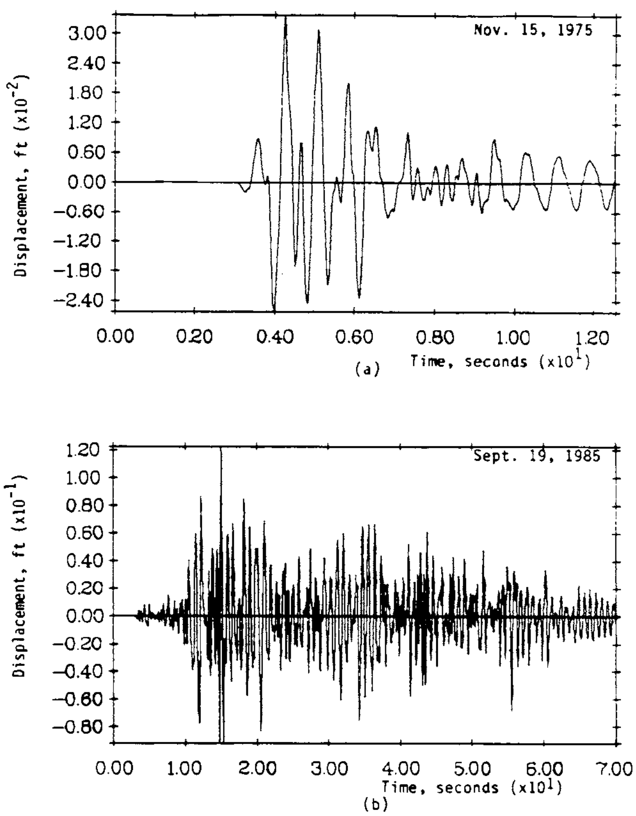

Figure 11. Computed displacement time history at the crest of La Villita; a) November 15, 1975; b) September 19, 1985.

Stick–slip response of other structures

Many structures may tend under the action of strong shaking to accumulate permanent stick–slip type deformation in a certain preferred direction [Yan; Succarieh, 1990]. In the case of such deformation in an earth dam, the upstream slope moves in the upstream direction and the downstream slope moves in the

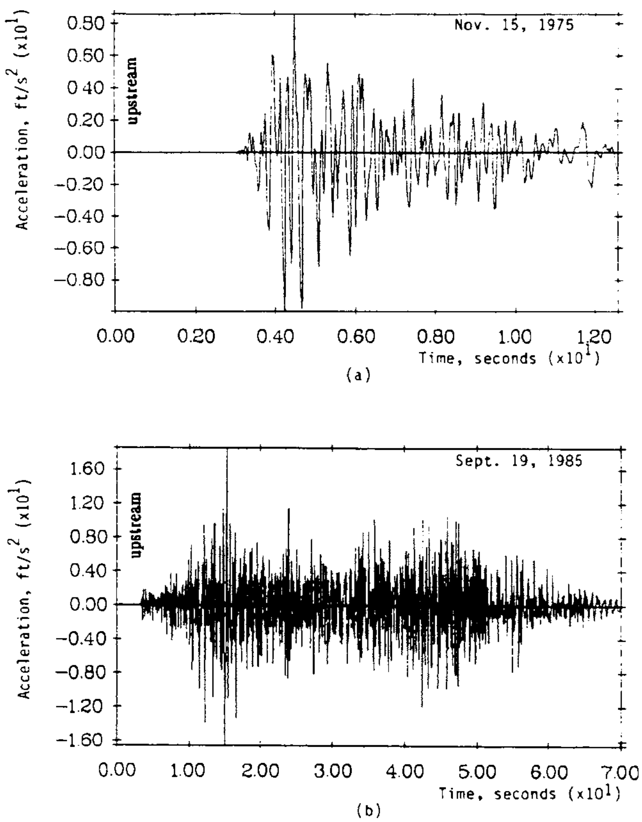

Figure 12. Computed acceleration time histor at the crest of La Villita; a) November 15 1975; b) September 19, 1985.

downstream direction. Backfill behind retainin walls will translate in the wall direction Mechanically stabilized walls (e.g. reinforce earth walls), marine loading quays, and natur and man–made slopes in general will also defor in a preferred direction. Accelerograph located on such structures (or accelerometers c corresponding small models), will recor asymmetric response such as that observed at th crest of La Villita, if and when stick–sli deformation takes place. No such respons appears to be documented for actual eart structures other than La Villita Dam Acceleration response in which slip–typ behavior is displayed exists however fo small–scale experimental models. Figures 15 an 16 depict two acceleration time historie recorded on an embankment and behind a retainin wall in centrifuge experiments [Bolton et al 1985; Dean et al, 1983]. Note the asymmetry i these acceleration histories and its resemblanc to that observed at La Villita. The recorde acceleration response at La Villita and th associated phenomena are consequently common t a large class of structures and are apt to occu in many other circumstances. The presence of strong motion instrument in these circumstance will provide additional valuable informatio concerning the occurrence of stick–sli permanent deformations.

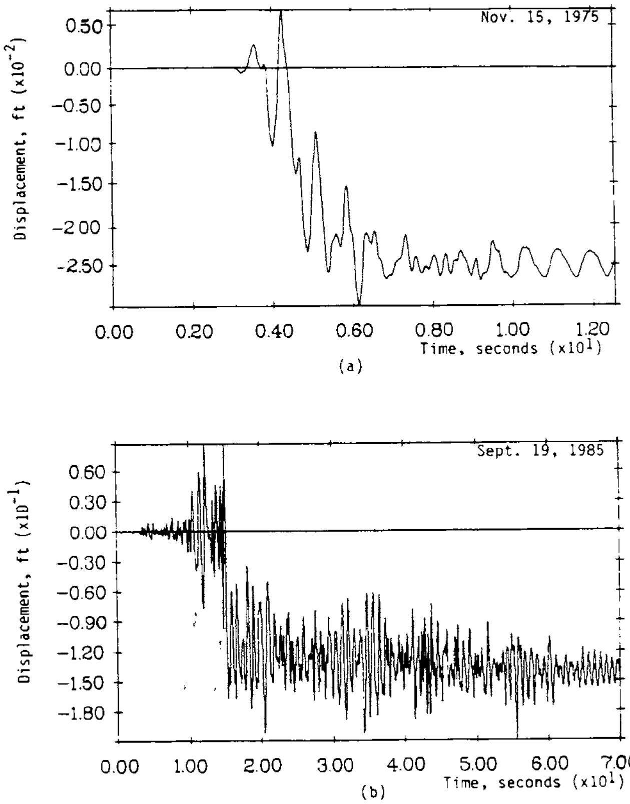

Figure 13. Displacement from Newmark analysis superimposed on calculated crest displacement; a) November 15, 1975; b) September 19, 1985.

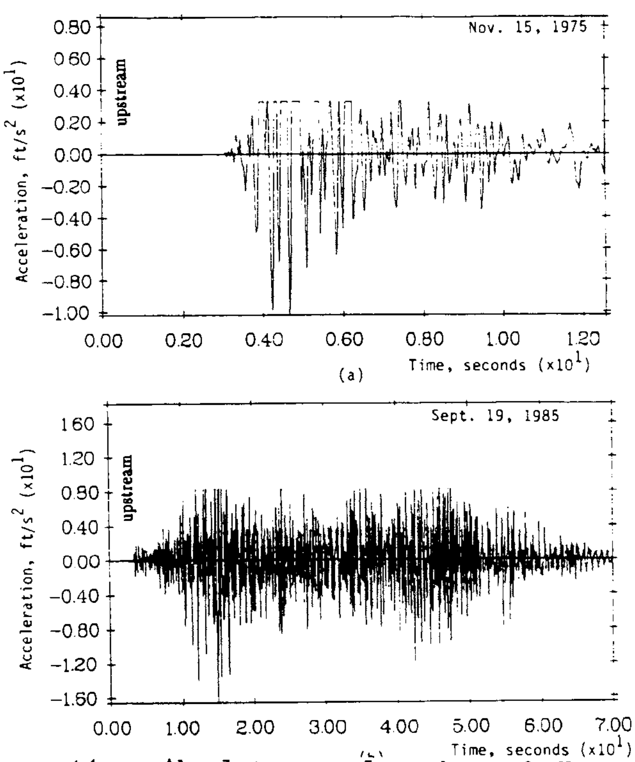

Figure 14. Absolute acceleration of Newmark sliding block: a) November 15, 1975; b) September 19, 1985.

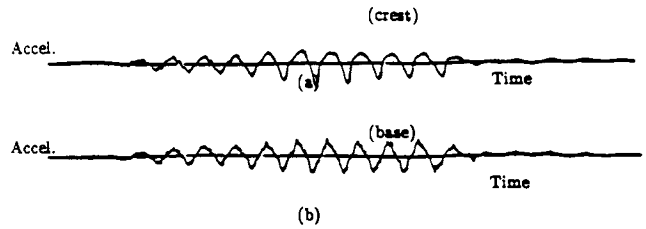

Figure 15. Recorded acceleration time history; centrifuge test on an embankment model: a) at the crest; b) at the base [Dean et al, 1983].

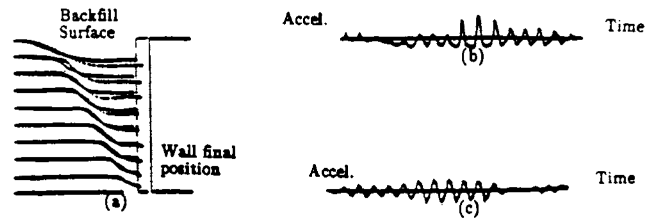

Figure 16. Recorded acceleration time history; centrifuge test on a retaining wall : a) within the failure wedge; b) at the base [Bolton et al, 1985].

SUMMARY AND CONCLUSION

La Villita Dam in Mexico has been exposed to a number of strong earthquakes during the period 1975–1985. Deformations due to these earthquakes are documented and crest acceleration time histories are also available. These acceleration records display an unusual asymmetric response pattern. This asymmetry may be attributed to the occurrence of localized stick–slip deformation below the recording instrument. Magnitudes of yield accelerations associated with the resulting sliding events depend on variations in the component of acceleration perpendicular to the failure surface and might not therefore be constant. Average values of yield accelerations associated with these slip events are inferred directly from the corresponding crest acceleration records. These yield accelerations are used in a sliding block formulation to compute the permanent horizontal displacement at the dam crest. Computed permanent displacements compare well with those actually observed. It is concluded that, in general, asymmetry in a recorded acceleration history may indicate the occurrence of yielding in a preferred direction (e.g. downslope in an earth embankment).

ACKNOWLEDGEMENTS

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Table 1. Observed behavior at La Villita Dam.

Earthquake	Peak Bedrock Accel. ft/sec^2	Avg. Yield Accel. ft/sec^2	Crest Hor. Disp. ft
11-15-75	1.345	3.281	0.053
09-19-85	3.87	8.2	0.182

REFERENCES

Bolton, M.D. and Steedman, R.S., 1985, "Modeling the Seismic Resistance of Retaining Structures," Xth Int'l Conf. on Soil Mech. and Found. Engrg., San Francisco.

Dean, E.T.R. and Schofield, A.N., 1983,"Two Centrifuge Model Tests: Earthquakes on Submerged Embankments," Report No. CUED/D-Soils/TR 134, Cambridge, England.

Comision Federal De Electricidad, 1980 "Performance of El Infiernillo and La Villita Dams Including the Earthquake of March,14 1979," February.

Comision Federal De Electricidad, 1985, "Behavior of Dams Built in Mexico (1974-1984)," XV Intl: Congress on Large Dams, Vol. 11, Lausanne, Switzerland.

Comision Federal De Electricidad ,1987, "Effects of the September 1985 Earthquakes on Dams Built on the Balsas River" Sym. on Dams and Earthquakes, China.

Elgamal, A.-W.M., Abdel-Ghaffar, A.M. and Prevost, J.H., 1988, "Elasto-Plastic Earthquake Shear-Response of One-Dimensional Earth Dam Models," Earthquake Engr. and Struct. Dynamics, Vol. 13, pp 617-633.

Elgamal, A.-W., Scott, R.F., Succarieh, M.F. and Yan, L.-P., 1990, "La Villita Dam Response During Five Earthquakes Including Permanent Deformation," Jour. of Geot. Engr., Vol. 116, No. 10, October.

Newmark, N.M., 1965, "Effects of Earthquakes on Dams and Embankments," Geotechnique 145(2), pp 139-160.

Newmark, N.M., 1959, "A Method of Computation for Structural Dynamics," J. of The Engr. Mech. Div., ASCE, pp 67-94.

Succarieh, M.F., 1990, "Estimation of Seismically induced Permanent Deformation in Earth Structures," Ph. D. Dissertation, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY, September.

Yan, L.-P., "Dynamic Stability Analysis of Earth Dams," Ph. D. Dissertation, Department of Civil Engineering, California Institute of Technology, Pasadena, CA, (in preparation).